CURRENT STATUS OF RARE KAON DECAY EXPERIMENTS AT BROOKHAVEN

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ABSTRACT

Results from three of the rare kaon decay experiments under way at the Brookhaven AGS are reviewed. The current status and future plans of these experiments are discussed.

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1. Introduction

Rare kaon decay experiments have provided important insights into the development of the Standard Model, and by pushing searches to even smaller branching ratios, can continue to do so. By searching for processes that are forbidden in the Standard Model, or by seeking decays that can only be mediated by higher order interactions, kaon decays can provide a low energy window into the high energy frontier. Many experiments in the last decade have sought to take advantage of the high flux of charged and neutral kaons available at the Brookhaven AGS. Modern electronic detectors coupled with improved beam lines can make it possible to search for decays with branching ratios less than 10^{-10}. As the AGS Booster becomes available, and secondary beamlines are upgraded, even smaller branching ratios will become reachable.

Three experiments with recent results and plans for upgrades will be reviewed. Two of the experiments seek lepton number violating processes. In a neutral beam, Experiment 791 has pressed a search for $K_L^0 \to \mu^\pm e^\mp$ below 10^{-10}, while for charged kaons, Experiments 777 and its successor, 851, have reached a sensitivity of about 2×10^{-10}. Experiment 791 has also accumulated a large sample of $K_L^0 \to \mu^+\mu^-$ decays. This decay, whose small branching ratio was an important early clue to the Glashow-Iliopoulos-Maiani, (GIM) mechanism,[1] may now be able to provide further sensitive tests of the Standard Model. Experiment 777 has pushed corresponding searches for the decays of the charged kaon, accumulating a large sample of $K^+ \to \pi^+e^+e^-$ decays. Experiment 787 is primarily a search for the decay $K^+ \to \pi^+\nu\bar{\nu}$, which occurs in the Standard Model at a branching ratio of about 2×10^{-10}. This process, which is extraordinary in its insensitivity to messy hadronic physics, can also provide an excellent window to much higher energies. This search has so far reached a sensitivity of nearly 5×10^{-9}.

All three experiments have achieved the goals set in their original proposals, and have all been approved for another round of experiments with upgraded or rebuilt detectors and beamlines. This next generation of rare kaon decay experiments will be the first to use the capabilities of the AGS Booster project, which will increase the intensity of the primary proton beam by a factor of four by 1995.

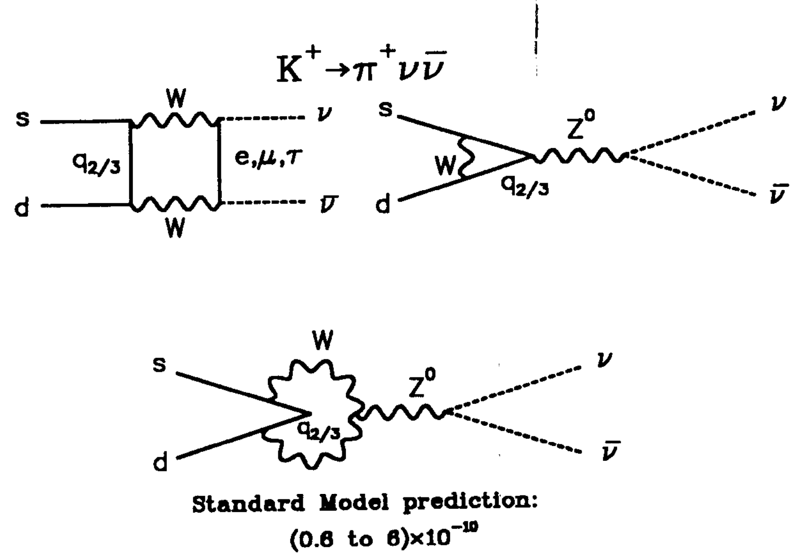

Figure 2.1: Feynman diagrams which contribute to the decay $K^+ \to \pi^+\nu\bar{\nu}$ in the Standard Model.

2. Experiment 787 and the Search for $K^+ \to \pi^+\nu\bar{\nu}$

Experiment 787 at the AGS was approved in 1984 to extend the search for $K^+ \to \pi$ by nearly three orders of magnitude, from a previous limit of 1.4×10^{-7} set by an experi at KEK.[2] This experiment is a collaboration among Brookhaven, Princeton University, TRIUMF.[3] Experimentally, the search is daunting: seeking a decay with a single cha track in the presence of millions of decays, most of which also result in single cha tracks.

2.1 $K^+ \to \pi^+\nu\bar{\nu}$ in the Standard Model

The Standard Model prediction of $K^+ \to \pi^+\nu\bar{\nu}$ is based on a calculation[4] of second order weak interaction, with loops involving heavy charge 2/3 quarks, as sh in the Feynman diagrams in Fig. 2.1. In addition to providing new information on Cabibbo-Kobayashi-Maskawa matrix elements in the Standard Model, it is sensitiv new, light scalar particles.

Wolfenstein[5] has expressed the CKM matrix

$$\begin{pmatrix} V_{ud} V_{us} V_{ub} \\ V_{cd} V_{cs} V_{cb} \\ V_{td} V_{ts} V_{tb} \end{pmatrix}$$

in the following parameterization in powers of the Cabibbo angle, λ:

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where the CP violating phase is represented by the (ρ, η) point in the complex plane.

The branching ratio for $K^+ \to \pi^+\nu\bar{\nu}$ is given in the Standard Model for three light neutrino types as[4,6]

$$B_{K^+\to\pi^+\nu\bar{\nu}} = \frac{3\alpha^2 B_{K^+\to\pi^0 e^+\nu}}{8\pi^2 \sin^4\theta_W} \frac{| V_{cs}^* V_{cd} D_c + V_{ts}^* V_{td} D_t |^2}{| V_{us} |^2} .$$

In the Wolfenstein parameterization of the CKM matrix, some algebraic manipulation can show that this implies

$$\frac{B_{K^+\to\pi^+\nu\bar{\nu}}}{B_{K^+\to\pi^0 e^+\nu}} \cdot \frac{8\pi^2\sin^4\theta_W}{3\alpha^2} \cdot \frac{1}{A^4\lambda^8 D_t^2} = \eta^2 + \left(1 + \frac{(1-\lambda^2/2)}{A^2\lambda^4}\frac{D_c}{D_t} - \rho\right)^2$$

which is a circle in the $\rho - \eta$ plane, with center on the ρ axis at

$$\rho = 1 + \frac{(1-\lambda^2/2)}{| V_{ts} |^2}\frac{D_c}{D_t}$$

and radius

$$\frac{1}{| V_{ts} |^2 D_t}\sqrt{\frac{B_{K^+\to\pi^+\nu\bar{\nu}}}{2.11\times 10^{-6}}}$$

where I have taken $\sin^2\theta_W = 0.23$, $\alpha(m_W) = 1/128$, and $B_{K^+\to\pi^0 e^+\nu} = 0.0482$, and the kinematic function D is given by

$$D(x) = \left(1 + \frac{3-(4-x)^2}{(1-x)^2}\right)\frac{x\ln x}{8} + \frac{x}{4} - \frac{3x}{4(1-x)}$$

with $x = m_{q_{2/3}}/m_W$, and D_c and D_t are values for the charm and top quark, respectively.

Thus, a measurement of $K^+ \to \pi^+\nu\bar{\nu}$ determines a circle in the $\rho - \eta$ plane which is centered on the ρ axis, displaced slightly from the point (1,0) by the charm quark contribution to the branching ratio, with a distance from that point that decreases with increasing $| V_{ts} |$ or increasing top quark mass (since the function D is monotonically increasing with top quark mass). The radius grows as the square root of the measured branching ratio, and varies with the same dependence on $| V_{ts} |$ and top quark mass as the displacement of the center.

The QCD radiative corrections to $K^+ \to \pi^+\nu\bar{\nu}$ have been calculated recently.[7] The effect is roughly to scale the charm quark contribution represented by D_c by 0.71. This does not change the geometric interpretation of the branching ratio, but does directly reduce the displacement of the center from (1,0) by that factor. I have scaled D_c by 0.71 to take account of QCD radiative corrections. The expected branching ratio as a function of top quark mass is shown in Fig. 2.2. The uncertainty in CKM matrix elements corresponds to the band of upper and lower limits as a function of top quark mass.

Upper limits on the branching ratio of $K^+ \to \pi^+\nu\bar{\nu}$ define the boundary of a circular region in the $\rho - \eta$ plane which must contain the value of ρ and η chosen by nature. The lower limit on the top quark mass of 89 GeV/c^2 from CDF[8] and the minimum value of $| V_{ts} |$ are also necessary assumptions to define the circumscribed region. Since the present upper limit is more than an order of magnitude from the prediction of the Standard Model, it is not surprising to find that the region provides no new constraint. Fig. 2.3 shows the regions allowed by Asano at KEK,[2] the Brookhaven E-787 published limit from data taken in 1988,[9] and a preliminary result from data taken by E-787 in 1989.[10] The region predicted by the Standard Model is just a dot near the center on this scale.

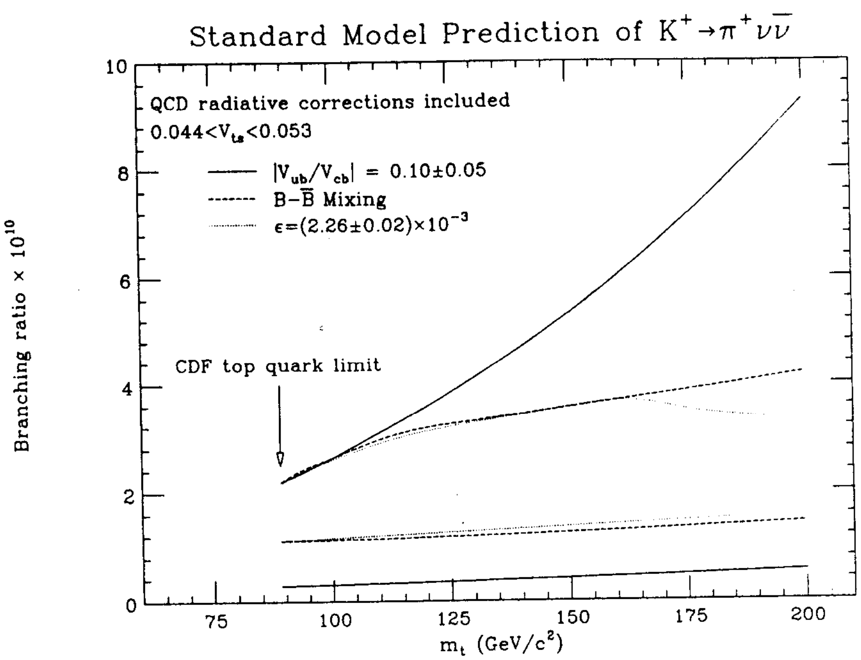

Figure 2.2: Expected branching ratio for the process $K^+ \to \pi^+ \nu \bar{\nu}$ in the Standard Model shown with and without QCD radiative corrections.

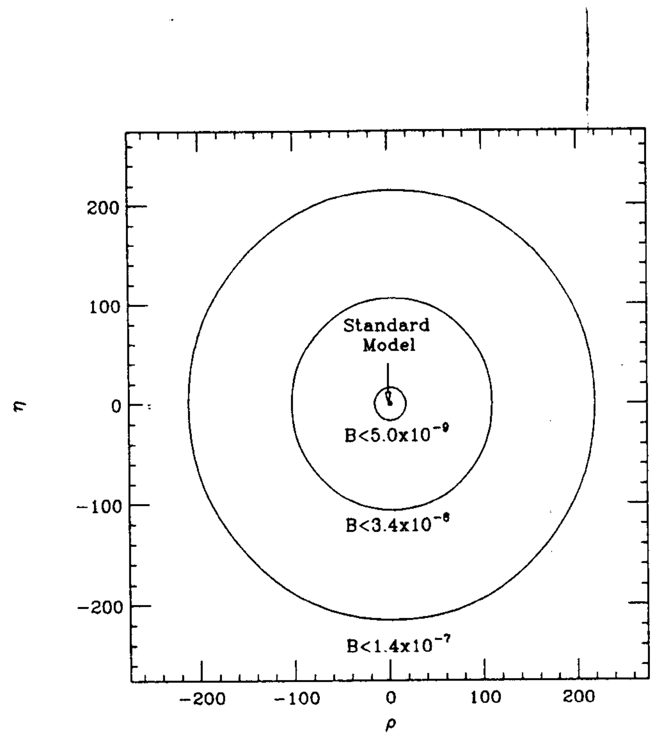

Figure 2.3: Regions of the $\rho-\eta$ plane determined by the KEK experiment,[2] the published Brookhaven result,[9] and a preliminary result from Brookhaven. The region expected in the standard model is in the small circle near the origin.

Fig. 2.4 show the annular region determined by a measurement of $K^+ \to \pi^+ \nu \bar{\nu}$, assuming a top quark mass of 140 GeV/c^2. The parameter $| V_{ts} |$ has been allowed to vary between 0.044 and 0.053 in the five nearly concentric circles. The annular region centered on the origin is determined[11] by present knowledge of $b \to u$ compared to $b \to c$ transitions.

For comparison with the region determined by $K^+ \to \pi^+ \nu \bar{\nu}$ shown in Fig. 2.4, some of the constraints[11] from other experiments are shown in Fig. 2.5. The lines shown are the central value and one standard deviation error on the measured quantities. The following processes are shown:

- The magnitude of V_{ub}/V_{cb}, which with one standard deviation errors, defines an annular region centered on the origin.
- Circles centered on (1,0) with radius dependent on the top quark mass, determined by $B - \bar{B}$ mixing.
- Hyperbolas with focus (1,0) determined by the CP violating parameter ϵ which describes the main features of CP violation in the K system.

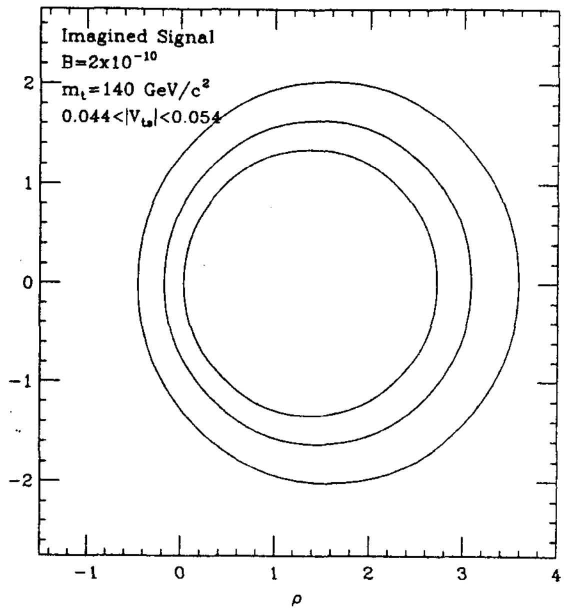

Figure 2.4: Region which would be determined by a measurement of a branching ratio of 2×10^{-10} for $K^+ \to \pi^+\nu\bar{\nu}$, assuming a top quark mass of 140 GeV/c^2, and allowing $0.044 <| V_{ts} |< 0.053$.

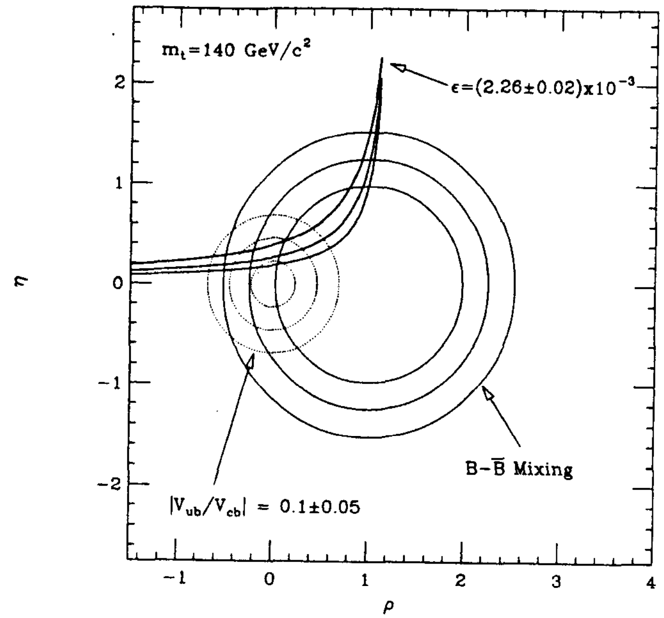

Figure 2.5: Regions of the $\rho - \eta$ plane determined by $| V_{ub}/V_{cb} |$, $B - \bar{B}$ mixing, and ϵ'/ϵ, assuming a top quark mass of 140 GeV/c^2 and Standard Model parameters as used in Fig. 2.4.

Not shown in this plot are a constraint from $K_L^0 \to \mu^+\mu^-$, discussed later, and the constraint from the recent measurements of ϵ'/ϵ, which is directly proportional to η.

2.2 The Experimental Search for $K^+ \to \pi^+\nu\bar{\nu}$

In order to observe such a rare decay, it is necessary to be able to differentiate kaon decay modes in a very intense beam. The beam used by Experiment 787 is a low energy electrostatically separated beam which can transport around 0.5×10^6 kaons per spill to the detector. In order to simplify the kinematics of kaon decay, the kaons are stopped in a fully active scintillating fiber target, so that common decay modes, like $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$, result in monoenergetic charged particles which can be distinguished from the three body decay $K^+ \to \pi^+\nu\bar{\nu}$ by measuring the momentum and energy of charged particles. The charged particle has been required to have momentum and energy between the π^+ and μ^+ momentum and energy from $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$, respectively in the trigger and in offline data analysis. It has been estimated that about 17% of the $K^+ \to \pi^+\nu\bar{\nu}$ spectrum is in this region. Fig. 2.6 shows the spectrum expected from the three body $K^+ \to \pi^+\nu\bar{\nu}$ decay, as well as the backgrounds from less rare decays modes.

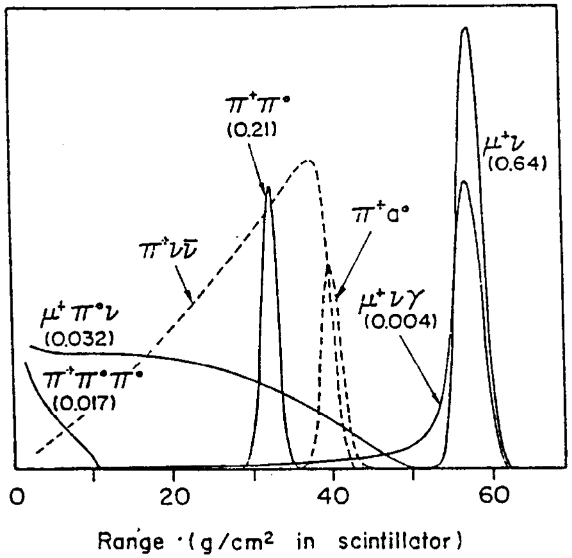

Figure 2.6: Range spectrum expected for the decay $K^+ \to \pi^+\nu\bar{\nu}$ compared to other decay modes. Experiment 787 is designed to be primarily sensitive to the kinematic region between the $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$ peaks.

Since the decay is so rare and the signature so easily confused with common decay modes, it is crucial to positively identify the charged particle as a pion and measure its energy and momentum accurately, and to eliminate any events with photon energy from $K^+ \to \pi^+\pi^0$ or radiative $K^+ \to \mu^+\nu$ decays. Particle identification is accomplished by stopping the decay products in scintillator. Correlation of range, momentum, and energy is used to tag muons from $K^+ \to \mu^+\nu$ and pions from $K^+ \to \pi^+\pi^0$ decays. Momentum is measured in a cylindrical drift chamber in a 1 T solenoidal magnetic field with $\sigma_p/p \sim 2.4\%$. Range stack scintillators give a range resolution of about 1.1 cm, and an energy resolution of about 3%. Using 500 MHz transient digitizers designed and built at Brookhaven,[12] the muon from pion decay can be observed in the range stack counter in which the pion stops, and much later, the positron from the muon decay can be identified. Lead-scintillator shower counters surround the entire detector, with an estimated inefficiency for missing a π^0 of $\leq 2.7 \times 10^{-6}$. The trigger and data acquisition system can handle instantaneous rates of several hundred kilohertz with acceptable deadtime and throughput.

The main improvements over previous experiments are increased solid angle, a magnetic field which allows momentum measurement for increased background rejection, a more intense beam, and improved instrumentation. The detector is shown in Fig. 2.7. The overall acceptance for $K^+ \to \pi^+\nu\bar{\nu}$ events was 0.55% for data taken in 1988, comes mainly from the solid angle (47%), kinematics (17%), timing requirements on K, π, and μ decay (32%), π^+ nuclear interaction and decay in flight (51%), and vetoing events with photon energy on accidentals (70%).

2.3 Experiment 787 Results

In 1988, data were taken for about two weeks at the end of the first run with the complete detector, with an exposure of 1.24×10^{10} K^+ stopping in the target. The acceptance was monitored with $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$ triggers. No events consistent with the decay $K^+ \to \pi^+\nu\bar{\nu}$ were observed, from which a limit[9] of $B(K^+ \to \pi^+\nu\bar{\nu}) \leq 3.4 \times 10^{-8}$ at the 90% confidence level was obtained.

Data taken in 1989 should be published soon, and analysis has begun of data taken in 1990 and 1991 in order to conduct a unified analysis of all data taken before the upgrade of the experiment and beam. A **preliminary** limit of $B(K^+ \to \pi^+\nu\bar{\nu}) \leq 5 \times 10^{-9}$ at the 90% confidence level has been obtained from data taken in 1989.

2.4 The Next Round of Experiment 787

In 1991, Experiment 787 was approved for a major upgrade. The centerpiece of the upgrade is a new beamline, which should be capable of delivering more than a factor of two more kaons per pulse, with much larger K/π ratio. The new beamline, with two stages of electrostatic separation and increased acceptance, is to be ready for testing in May, 1992. As the AGS Booster becomes operational, another increase in flux of a factor of three or four can be expected, beginning in 1993. At the same time, detector upgrades to take advantage of the increased kaon flux were undertaken.

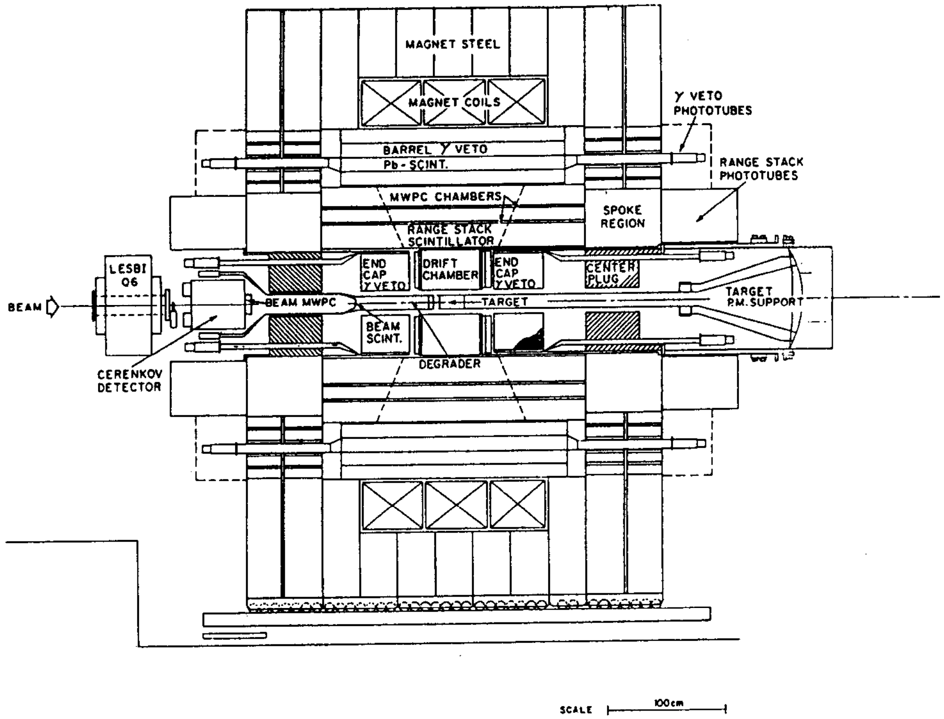

Figure 2.7: The Experiment 787 detector. From the center, kaons stop in a scintillating fiber target, charged tracks are observed in the cylindrical drift chamber, and range and energy are measured in the range stack scintillators. Around the whole apparatus, lead-scintillator photon vetoes are arrayed.

Detector upgrades are designed with two things in mind. First, the trigger and data acquisition systems must be capable of handling the higher rates of the new beam. Second, the detector must be capable of background rejection at the higher sensitivity which is anticipated. At the same time, the improved background rejection cannot be allowed to compromise the detection efficiency for $K^+ \to \pi^+ \nu \bar{\nu}$ by random vetoing.

To this end, the trigger system has been partially rebuilt, moving trigger decisions to earlier levels in order to reduce deadtime. A custom IC is being developed for the Transient Digitizers to detect the muon from pion decay, which will be as much as five times faster than the RISC microprocessor (an AMD 29000) used previously. The data acquisition system is being upgraded from a VAX hosting a farm of FERMILAB ACP 68020 processors to a Silicon Graphics multiprocessor Unix system. A high speed FASTBUS interface to VME is being developed to acquire data into the multiprocessor system as quickly as possible.

Work is also underway to build improved versions of the scintillating fiber target and the inner drift chamber. New square fibers can be packed into the target with much less dead material, and the new fibers produce more than a factor of two more light than the old. A new central drift chamber is under construction at TRIUMF, which should have substantially less mass than the old chamber. These improvements should improve the energy and momentum resolution, which translates into improved background rejection. Replacing or augmenting the lead-scintillator shower counters with a system of CsI crystals is being considered to reduce the π^0 inefficiency still further.

3. Lepton Number Violating Decays

Two of the experiments being considered, Experiments 777 and 791, are optimized for searching for lepton number violating decays. Aside from the attraction of performing a stringent test of a very fundamental conservation law, this kind of search is a window on new interactions among particles mediated by extremely massive particles.

The argument is based on the calculation of the diagrams shown in Fig. 3.1. For a very massive particle X which couples with strength g at each vertex, the branching ratio is proportional to g^4/m_X^4. Of course, the precise couplings are only predicted by a complete theory.

Scaling from a weak decay like muon decay, mediated by a W, a branching ratio of 10^{-10} corresponds to an exchanged particle of around 70 TeV/c^2. Thus, observation of such a rare decay would suggest new dynamics at a very large mass scale, which would be exciting indeed.

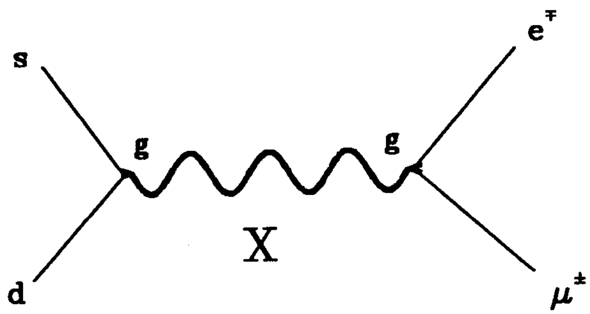

Figure 3.1: Feynman diagram for a very massive particle X which couples with strength g at each vertex.

4. Experiment 777 and the Search for $K^+ \to \pi^+\mu^\pm e^\mp$

AGS Experiment 777, a collaboration among Brookhaven, FERMILAB, PSI, University of Washington at Seattle, and Yale University,[13] was primarily an attempt to search for the lepton number violating decay $K^+ \to \pi^+\mu^\pm e^\mp$ and study the decay $K^+ \to \pi^+e^+e^-$.

4.1 The Experimental Search for $K^+ \to \pi^+\mu^\pm e^\mp$

Decays in flight of an incident 5.8 GeV unseparated K^+ beam were observed. A flux of about 10^7 kaons per one second spill (along with around 20 times as many pions and protons) decayed in a 5 m long vacuum box. About 10% of the incident kaons decayed in the vacuum box; the remainder passed through the deadened central region of the detector. Charged particles were bent twice in opposite directions; the first bend served to direct oppositely charged particles to two distinct sides of the detector; the second dipole and four stations of proportional wire chambers were used to measure the momentum of charged tracks. The momentum resolution of the spectrometer (in GeV/c) was $\sigma_p = 0.01p^2$ from 0.6 to 4.0 GeV/c. The layout of the detector is shown in Fig. 4.1.

The detector was optimized for observation of the decay $K^+ \to \pi^+\mu^\pm e^\mp$. Electrons were identified by requiring hits in two hydrogen threshold Cerenkov counters and requiring

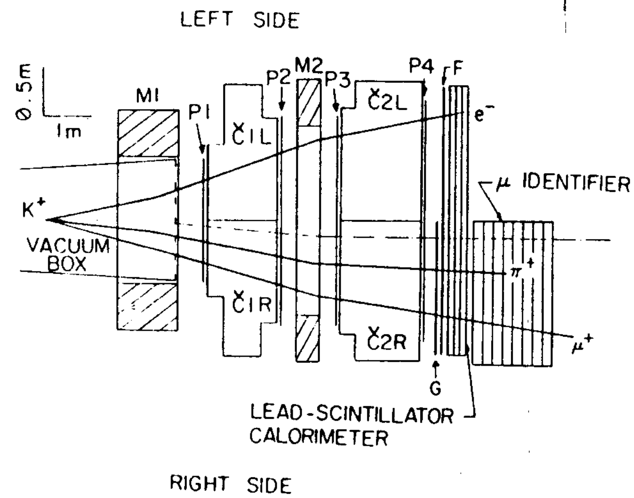

Figure 4.1: Experiment 777 apparatus.[14] M1 and M2 are dipole magnets.

that the energy deposition in a lead-scintillator show counter following the last proportional chamber be consistent with an electron. On the other half of the detector, two Cerenkov counters filled with CO_2 had a threshold near the cutoff of the muon spectrum from $K^+ \to \pi^+\mu^\pm e^\mp$ at 3.7 GeV/c. The logical OR of these two counters was 99.9% efficient at rejecting positrons. Behind the shower counter was a muon detector made from steel plates and proportional tubes.

The trigger for $K^+ \to \pi^+\mu^\pm e^\mp$ initially required three charged tracks as measured with scintillation counter hodoscopes and a potential muon track in the muon detector and an electron candidate in the hydrogen Cerenkov counters. About 250 such events per spill were read into 68020 microprocessors (FERMILAB ACP nodes) which were programmed to find three acceptable tracks with an distance of closest approach to a common vertex of less than 10 cm (about 10 sigma), rejecting 95% of the triggers. About 3×10^7 events were written on tape for analysis offline.

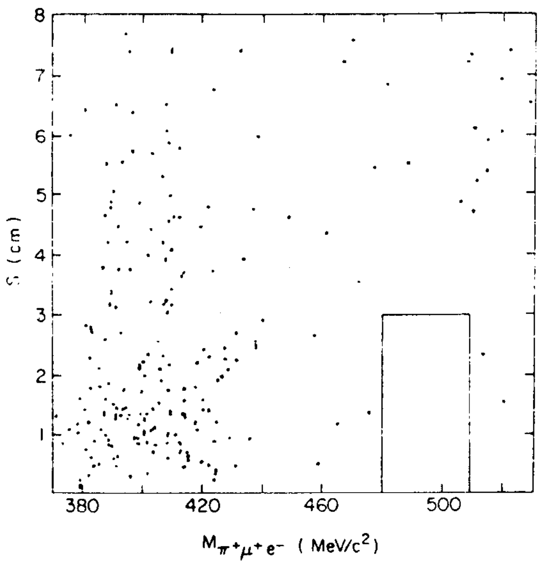

Figure 4.2: Distance of closest approach of the three tracks to a common vertex (S) versus invariant mass of the three charged particles.[14] No candidates are seen in the signal region (the box), leading to a limit of 2.6×10^{-10} at the 90% confidence level from these data. Combining these data with all other Experiment 777 and 851 data leads to a limit of 2.1×10^{-10} at the 90% confidence level.

4.2 Experiment 777 Results

Offline, the track parameters were measured and particles were identified by means of the Cerenkov counters, the muon detector, and the lead-scintillator calorimeter. The detection and rejection efficiencies were monitored by a sample of $K^+ \to \pi^+\pi^+\pi^-$ and Dalitz decays. The events that survive are shown in Fig. 4.2, where the vertical axis is the distance of closest approach to a common vertex. No events consistent with the decay $K^+ \to \pi^+\mu^\pm e^\mp$ were observed.

From all data taken by Experiment 777 (and 851, an extension), a limit $B(K^+ \to \pi^+\mu^\pm e^\mp) \leq 2.1 \times 10^{-10}$ at the 90% confidence level was set.[14] This is an improvement of a factor of 23 over the previous limit.[15]

Recently, an analysis of a search for $K^+ \to \pi^+e^+e^-$ has resulted in a sample of approximately 500 candidate events.[16] This analysis increases by nearly an order of magnitude the number of observed events. A **preliminary** branching ratio derived from these events is $(2.75 \pm 0.23 \pm 0.13) \times 10^{-7}$.

4.3 The Next Round: Experiment 865

To take advantage of the higher intensity possible with the AGS Booster, a new experiment was designed, and has been approved. the collaboration was expanded to include Basel, Brookhaven, INR Moscow, JINRT Dubna, New Mexico, Pittsburgh, PSI, Tbilisi, Yale, and Zurich.

The goal is to push the search for $K^+ \to \pi^+\mu^\pm e^\mp$ from the present 90% confidence limit set by Experiment 777 of 2.1×10^{-10} to $\sim 3 \times 10^{-12}$. This will require that the AGS Booster can deliver 1.2×10^{13} protons per pulse on the production target; that is similar to the total number of protons per pulse available to all experiments without the Booster. About 50,000 $K^+ \to \pi^+e^+e^-$ decays should be observable with this detector. A similar sample of the decay $K^+ \to \pi^+\mu^+\mu^-$ should be observable, possibly allowing study of the polarization of the μ^+. Measurement of the CP violating component of the polarization would be a sensitive test of the Standard Model, although the polarization is expected to be small.

To carry out this experiment, a new, more intense K^+ beam has been built at Brookhaven. This new 6 GeV/c unseparated beam should be better collimated than its predecessor, and deliver seven times as many kaons (assuming 1.2×10^{13} protons on target).

The apparatus will be enlarged for increased acceptance. The main spectrometer magnet will have a 50 inch gap, compared to its 30 inch predecessor. The new, larger chambers will be designed with four planes per station, which should improve their efficiency. These

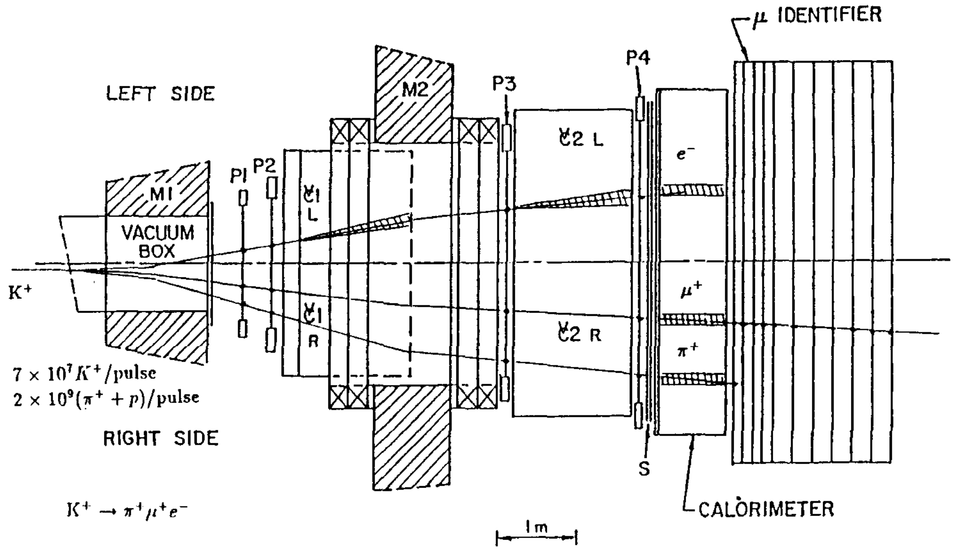

Figure 4.3: Experimental apparatus to be used by Experiment 865 in the search for $K^+ \to \pi^+\mu^\pm e^\mp$. Much of the acceptance gain over Experiment 777 is due to the increased aperture of the M1 magnet.

improvements should lead to an increased sensitivity of about 4.5 over the previous experiment. The remainder of the factor 70 improvement (about a factor of 2.3) is expected to come from longer running periods. Fig. 4.3 shows the layout of the new detector.

5. Experiment 791 and the Search for $K_L^0 \to \mu^\pm e^\mp$

Experiment 791 was designed to extend the search for $K_L^0 \to \mu^\pm e^\mp$, the lepton number violating decay of the neutral kaon, to a branching ratio of around 1×10^{-10}. This experiment is a collaboration among the University of California at Irvine, UCLA, Los Alamos National Laboratory, Stanford University, Temple University, the University of Texas at Austin, and the College of William and Mary.[17] This experiment used a clean, high intensity neutral beam coupled to a modern detector with excellent timing, an efficient and high speed trigger and data acquisition system, excellent particle identification, particularly of muons, and a high resolution spectrometer.

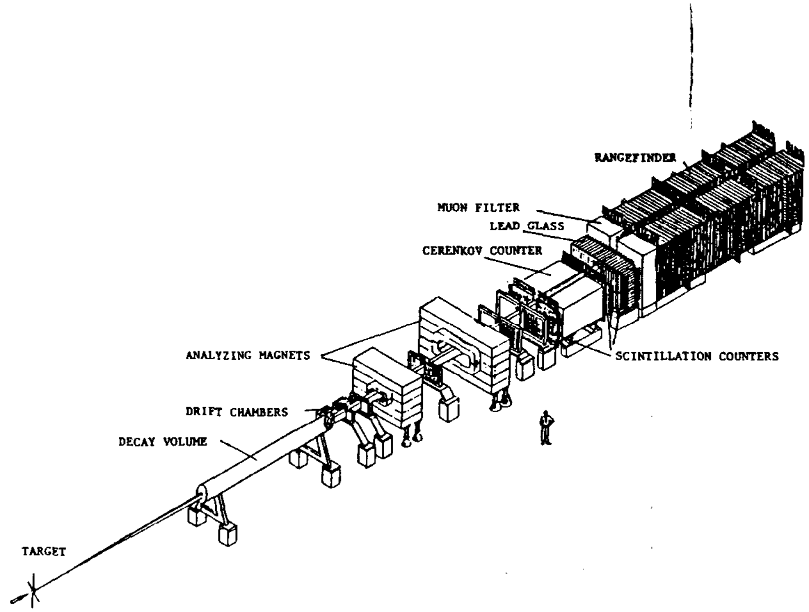

Figure 5.1: View of the Experiment 791 detector.

5.1 The Experimental Search for $K_L^0 \to \mu^\pm e^\mp$

The experiment is in the B-5 neutral beam. Sweeping magnets removed most of the charged particles from the beam, and decays occurred in an 8 m vacuum tank. A two magnet spectrometer downstream of the decay region makes two independent measurements of the decay product's momentum, with two equal and opposite 300 MeV/c kicks. Behind the spectrometer, a Cerenkov counter and 13.8 radiation length lead-glass shower counter were used for for electron identification. A 91 cm iron wall and scintillation hodoscope, and a rangefinder consisting of marble and aluminum plates with proportional tubes interspersed served to identify muons. Fig. 5.1 shows the layout of the detector.

The trigger requires tracks in both spectrometer arms as determined by the scintillator hodoscopes. Dilepton triggers require coincident hits in the Cerenkov counters or the muon hodoscope.

The final analysis of all Experiment 791 data is still in progress; however, a **preliminary** result[18] has been presented that $B\,(K_L^0 \rightarrow \mu^{\pm}e^{\mp}) \leq exp6.1{-}11$ from data taken in 1988 through 1990.

5.2 Measurement of B($K_L^0 \rightarrow \mu^+\mu^-$)

Recently, Experiment 791 has reported a new **preliminary** measurement of the branching ratio for $K_L^0 \rightarrow \mu^+\mu^-$.[19] Offline, events were required to have two well measured positively charged tracks which do not traverse material or magnetic fields near the coils which originate in the fiducial decay volume. Particle identification using the Cerenkov counters, the lead glass array, and the rangefinder was then applied to classify the decays as $K_L^0 \rightarrow \mu^{\pm}e^{\mp}$, $K_L^0 \rightarrow \mu^+\mu^-$, and $K_L^0 \rightarrow e^+e^-$ candidates. A sample of $K_L^0 \rightarrow \pi^+\pi^-$ events was selected from minimum bias triggers and analyzed similarly to normalize the experiment. The final sample of $K_L^0 \rightarrow \mu^+\mu^-$ candidates is shown in Fig. 5.2, a scatter-plot of the $\mu^+\mu^-$ mass against θ, the angle between the line from the target to the decay point and the reconstructed kaon momentum vector. For a two body decay, θ should be near zero. The background from the decay $K_L^0 \rightarrow \pi^{\pm}e^{\mp}\nu$ can be estimated by examining events with a larger value of θ, and identifying electrons with the Cerenkov counters and lead-glass array.

The **preliminary** result is a signal of 349 $K_L^0 \rightarrow \mu^+\mu^-$ decays over a background of 23. Normalizing to $K_L^0 \rightarrow \pi^+\pi^-$, this results in a branching ratio of $(6.96 \pm 0.40 \pm 0.22) \times 10^{-9}$.

These measurements are consistent with a branching ratio of $(7.0 \pm 0.4) \times 10^{-9}$.

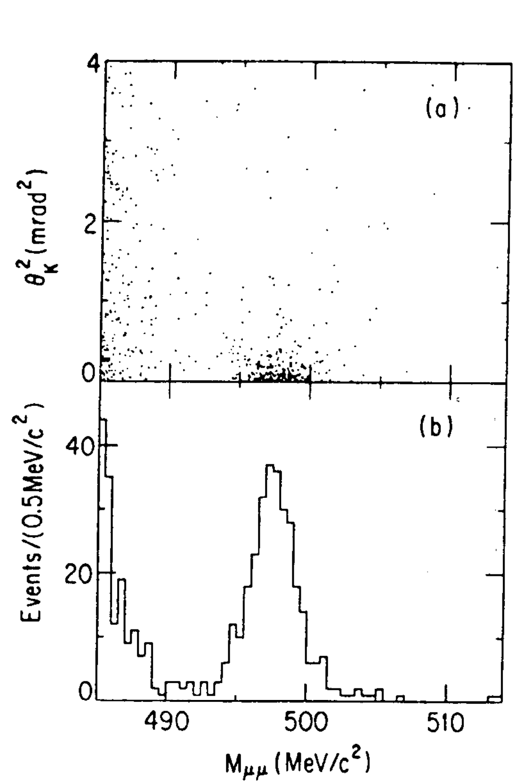

Figure 5.2: a) Scatterplot of the invariant mass of the reconstructed $\mu^+\mu^-$ pair plotted against the colinearity angle of the decay. The cluster of events at small θ near the K^0 mass (498 MeV/c^2) is the observed signal. b) The invariant mass of $K_L^0 \rightarrow \mu^+\mu^-$ candidates with $\theta^2 \leq 2 \times 10^{-6}$.[20]

Table 5.1: $K_L^0 \rightarrow \mu^+\mu^-$ branching ratio as measured by Experiment 791.[20]

Year	Events	Branching ratio
1988	88	$(5.8 \pm 0.6 \pm 0.4) \times 10^{-9}$
1989	281	$(7.6 \pm 0.5 \pm 0.4) \times 10^{-9}$
1990	349	$(6.96 \pm 0.40 \pm 0.22) \times 10^{-9}$

5.3 $K_L^0 \to \mu^+\mu^-$ in the Standard Model

In the Standard Model, the real part of the amplitude for $K_L^0 \to \mu^+\mu^-$ is dominated by interesting electroweak (or short distance) diagrams analogous to those in Fig. 2.1, while the imaginary part is dominated by a boring 2-γ (or long distance) intermediate state. The long distance part can be estimated from the measurement of $K_L^0 \to \gamma\gamma$ and QED, which gives a branching ratio of 6.83×10^{-9}, and is the minimum rate at which $K_L^0 \to \mu^+\mu^-$ should occur in the Standard Model. One can then attempt to interpret any excess of the branching ratio over this value, called the unitarity bound, as due to the short distance contribution.

The short distance part of the branching ratio for $K_L^0 \to \mu^+\mu^-$ is given in the Standard Model as[6]

$$B_{K_L^0\to\mu^+\mu^-} = B_{K^+\to\mu^+\nu}\frac{\tau_{K_L^0}}{\tau_{K^+}}\frac{\alpha^2}{4\pi^2\sin^4\theta_W}\frac{Re\,(V_{cs}^*V_{cd}C_c + V_{ts}^*V_{td}C_t)^2}{V_{us}^2}.$$

In the Wolfenstein parameterization of the CKM matrix. this can be written as

$$\sqrt{\frac{B_{K_L^0\to\mu^+\mu^-}}{B_{K^+\to\mu^+\nu}}\frac{\tau_{K^+}}{\tau_{K_L^0}}\frac{4\pi^2\sin^4\theta_W}{\alpha^2}} = C_c + A^2\lambda^4 C_t(1-\rho)$$

or

$$\sqrt{\frac{B_{K_L^0\to\mu^+\mu^-}}{7.77\times 10^{-5}}} = C_c + \mid V_{ts}\mid^2 C_t(1-\rho)$$

where the kinematic functions C_c and C_t reflect the charm and top quark contribution. The charged and neutral K lifetimes are taken to be 12.37 ns and 51.8 ns, respectively, and the $K^+ \to \mu^+\nu$ branching ratio is taken to be 63.51%.

Subtracting the long distance contribution puts an upper limit on the branching ratio of 8×10^{-10} which makes a lower limit on ρ. With the top quark heavier than 89 GeV, and the Particle Data Group central value for $\mid V_{ts}\mid = 0.049$. this implies minimum values for ρ as shown in Table 5.2. Note. however. that the measurement of $K_L^0 \to \mu^+\mu^-$ is only half a standard deviation greater than the unitarity bound.

Table 5.2: Minimum values of ρ from $K_L^0 \to \mu^+\mu^-$ for various top quark masses.

m_t (GeV/c^2)	ρ_{min}
89	-1.04
100	-0.70
125	-0.20
150	0.01
175	0.29
200	0.42

5.4 The Next Round: Experiment 871

Experiment 791 also has a substantial upgrade planned to take advantage of the intensity which the AGS Booster will provide. This has been approved as AGS Experiment 871. The new experiment relies on using a beam stop inside the calorimeter to stop the neutral beam in order to reduce counting rates in detectors downstream of the plug due to K_L^0 decays. Beam tests have been carried out to make certain that rates from neutrons originating in the plug are not a problem.

The plan of the new experiment is shown in Fig. 5.3. The decay volume will be lengthened, and instrumented with a high precision tracking device. Scintillating fibers and straw tube drift chambers are being considered. The acceptance will be increased by more than a factor of two over experiment 791. Part of this will come from increasing the aperture of the upstream spectrometer magnet. Other detector components will be improved, based on knowledge gained in running Experiment 791. The dipoles will operate with opposing kicks, but will be tuned to make two body K_L^0 decays tracks parallel to the beam direction; this information will be used to form the Level 1 trigger.

This experiment should have an engineering run in 1993. and extended physics runs the next two years. The goal is to reach a single event sensitivity below 1×10^{-12} for the decay $K_L^0 \to \mu^\pm e^\mp$, and to accumulate of order 10,000 $K_L^0 \to \mu^+\mu^-$ events.

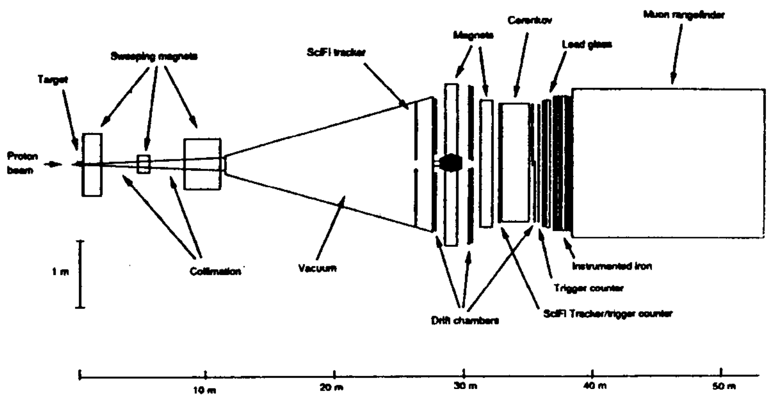

Figure 5.3: Proposed configuration of Experiment 871. This experiment is designed to reach a sensitivity 30 times greater than Experiment 791 to the decay $K_L^0 \to \mu^{\pm} e^{\mp}$.

6. AGS Booster Project

The AGS Booster is a new synchrotron recently completed at Brookhaven which will eventually increase the AGS proton intensity by a factor of four, as well as having an essential role in the injection of heavy ions into RHIC. The 202 m circumference Booster ring consists of 36 2.34 m dipole magnets and 48 0.47 m quadrupole magnets. The radiofrequency and vacuum systems were innovative and ambitious designs in order to satisfy the requirements of intense proton beams and lower intensity heavy ion beams. The plan of the Booster is shown in Fig. 6.1, where the LTB (Linac-to-Booster) line is the where the 200 MeV proton beam from the Linac is injected into the Booster, and the BTA (Booster-to-AGS) line is where the Booster delivers four pulses at 1.5 GeV to the AGS. At the time of writing, the Booster has injected accelerated protons into the AGS, and commissioning is going very smoothly. The Booster will be in place for the 1992 run of the AGS, and as more RF is added in 1993 and 1994, the increased intensity will become available to experiments.

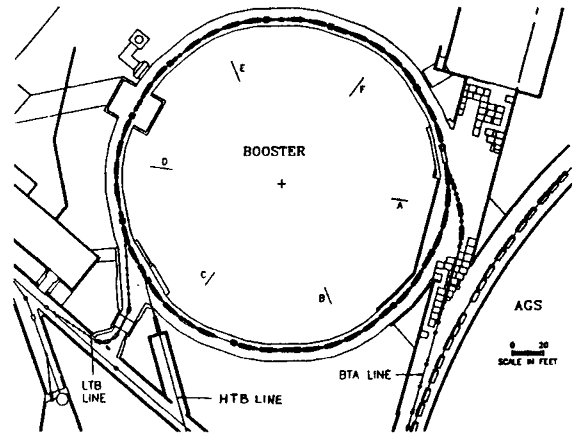

Figure 6.1: Layout of the AGS Booster.

7. Conclusion

The rare kaon decay program at Brookhaven is entering a new and exciting era in which a sample of events from very rare decays can be acquired. Substantially upgraded experiments, coupled with new beamlines which can take advantage of the increased proton intensity which should result from the AGS Booster project, will make gains of another order of magnitude or more possible in accessible branching ratios. In the next few years, these experiments should provide a fertile testing ground for the Standard Model, and some of the ideas which go beyond it.

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